LATE PLIOCENE VEGETATION AND CLIMATE CHANGE AT STONY CREEK BASIN, WESTERN UPLANDS OF VICTORIA, AUSTRALIA

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A high resolution pollen record from a small palaeo-lake in Victoria's western uplands provides evidence of vegetation and climate change during the latest Pliocene. A Late Pliocene age is indicated by both zircon fission track dating of lacustrine sediments, and comparison with regional palynostratigraphies. The 2.7m long sequence is dominated by fluctuating proportions of tree taxa indicative of a continuously forested environment, including rainforest taxa which are highly restricted or extinct regionally (*Phyllocladus*, *Podocarpus*, *Symplocos*, *Quintinia*, *Elaeocarpus*, *Macaranga/ Mallotus*, Cunoniaceae) or Australia-wide (*Dacrycarpus*, *Dacrydium*). *Eucalyptus* forest including a mesotherm rainforest angiosperm component dominates early in the sequence. Subsequent regional drying is indicated by the loss of rainforest taxa, increased representation of *Callitris* and lower lake levels. Towards the top of the sequence, Podocarpaceae and ferns, representative of microtherm rainforest, become major pollen and spore components. Bioclimatic preferences of modern relatives of the fossil rainforest types indicate that mean annual temperature during the early warm 'interglacial' interval may have been 3°C higher than today, and summer rainfall during intervals of both meso- and microtherm rainforest was probably higher than today.

Keywords: Late Pliocene, pollen analysis, Australia, palaeoecology

THE TIMING and nature of the profound changes to climate and vegetation that marked the transition from the Tertiary to the Quaternary between about 6 Ma and 1.8 Ma remain poorly understood (Kershaw et al. 1994a; Williams et al. 1998). Worldwide, the transition involved major reorganisations of atmospheric and oceanic heat transport patterns, with consequent climatic disruptions and species losses (Webb & Bartlein 1992). Patterns of change typical of large parts of the temperate zones in both northern and southern hemispheres included loss or range contraction of mesic taxa and their replacement by frost-, drought- (and in some areas, fire-) tolerant species (Williams et al 1998; Huntley & Webb 1988). In southeastern Australia, evidence from fossil pollen shows the loss of formerly widespread rainforest communities palynologically dominated by taxa such as *Nothofagus* (subgenus *Brassospora* Read and Hill) and Podocarpaceae, and their replacement by taxa characteristic of open-canopied communities including *Casuarina* or *Allocasuarina*, *Eucalyptus*, Poaceae and Asteraceae (Kershaw et al. 1994a; Macphail 1997).

Much of our understanding of the vegetation before, during and after this transition is derived from either detailed 'snapshot' studies of stratigraphically discontinuous, poorly dated, terrestrial sedimentary horizons using micro- and/ or macro-fossil plant assemblages (eg. Macphail et al. 1993, 1995), or fossiliferous terrestrial and shallow marine sedimentary sequences, such as found within the offshore Gippsland Basin (Stover & Partridge 1973; Macphail 1997) and the partly marginal marine Murray-Darling Basin (Martin 1987; Macphail & Truswell 1989, 1993; Macphail 1999) that provide long and better dated but coarse palynological records. Neither the 'snapshot' nor the stratigraphic approach has succeeded in elucidating the nature and composition of specific communities and their dynamic interactions in response to the pronounced cyclicity which was evidently a feature of global climate by the Late Pliocene (Shackleton et al. 1995).

This paper presents a pollen record from the upper part of a small Late Pliocene lake deposit in the western uplands of Victoria. The simple hydrological characteristics and small size of this palaeolake suggest that its pollen source area was quite limited (Jacobson & Bradshaw 1981; Prentice 1985; Jackson 1990), comparable in size to those of small lakes that have been important sources of high spatial and temporal resolution pollen data during the Late Quaternary on the western plains of Victoria (Kershaw et al. 1994a). Combined with this spatial resolution, relatively close sampling intervals used here allow the reconstruction of Late Pliocene vegetation history at a scale typical of Late Quaternary palaeoecology. Age determination has been facilitated by the presence within the basin of radiometrically datable zircons, allowing a comparison to be made with a biostratigraphic age estimate.

THE SITE AND ITS ENVIRONMENTAL SETTING

Stony Creek Basin (SCB) (37° 21' S, 144° 08' E) is situated at 550m above sea level (asl) in the western uplands of Victoria (Fig. 1). These subdued ranges, parts of the Delamerian and western Lachlan fold belts (Gray et al. 1997), are composed predominantly of steeply-folded early Palaeozoic marine sandstones and shales now elevated approximately 300-1000 m asl. The uplands, which divide the Victorian volcanic plains to the south from the Murray River plain to the north, have represented a topographic high since at least the Cretaceous (Jones & Veevers 1982). Although there is evidence for limited Pliocene-Pleistocene fault movement (Hughes et al. 1999), the uplands have occupied essentially their current altitudes since the Middle Miocene (Joyce 1992). Numerous Pliocene-Pleistocene basaltic lava and scoria cones form conspicuous geomorphic features of the southeastern corner of the western uplands (Joyce 1988); associated narrow valley lava flows, generally deeply weathered, interdigitate with the underlying folded Ordovician sediments. Phreatomagmatic maars are present but their tuffaceous deposits are typically partly or completely eroded (J. Hollis, unpub. data).

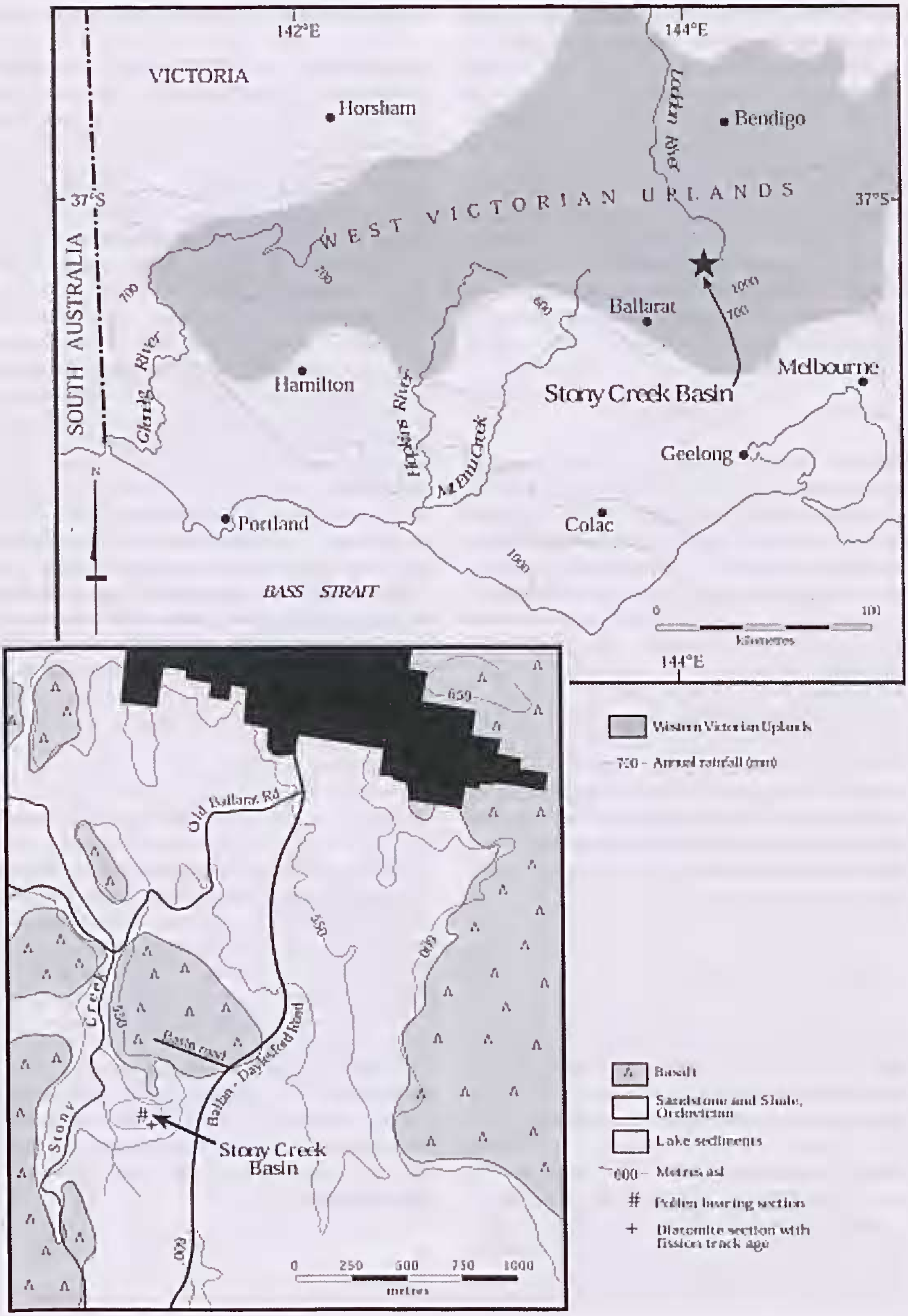
The climate of the region is controlled largely by the passage of subtropical high pressure anticyclones, which track over mainland southern Australia during autumn, winter and spring, but shift south of the continent during summer (Parkinson 1986). Low pressure fronts separating these anticyclones bring the majority of annual precipitation to the western uplands in the cooler months between April and November. The highest precipitation, up to about 1200 mm, falls on the most elevated parts of the continental divide in the southeastern corner of the western uplands, while as little as 400 mm falls on the northern and rainshadow parts of the southern margins. Annual rainfall and temperature at the Stony Creek Basin, seven km north of the continental divide, are estimated by BIOCLIM (Houlder et al. 2000) to be 870 mm, and 11° C, respectively.

Western uplands vegetation is predominantly *Eucalyptus* open woodlands and forests, with community type and species dominance controlled primarily by variations in altitude-dependent effective moisture budgets, and secondarily by soil type (Land Conservation Council 1987). Open box-ironbark woodlands in the driest, lowest areas give way to open gum-stringybark forests at better watered moderate elevations, and to damp sclerophyll forest (Conn 1993) in limited areas on and near the divide receiving more than 1000 mm annual precipitation. Tall open forest is nowhere well developed, and rainforest is absent entirely. Vegetation near Stony Creek Basin consists of *E. rubida-E. obliqua-E. radiata* open forests with grassy or heathy understoreys on duplex soils developed on Ordovician slopes, while deep krasnozems developed on basalt support *E. viminalis-E. obliqua* grassy open forests, most of which have been cleared for agriculture.

Stony Creek Basin is a flat-bottomed, roughly circular depression, its floor approximately 300 m in diameter. To the north and the west, rims 40 metres above the basin floor consist of erosional remnants of valley lava flows, while to the south and east they consist of ridges of Ordovician shale and sandstone. A small, seasonal stream, Stony Creek, flows along the western edge of the basin at the foot of the west rim and forms the only outlet from the basin.

The floor of the basin is partly mantled by ca. 2 m of mottled silt, sand and quartz gravel, much of which was removed during nineteenth century surface gold mining and later through development of the site as a motorcar racetrack. Beneath these mottled coarse textured deposits organic-rich, black, lacustrine silty clays containing wood fragments,

Fig. 1. Locality map of Stony Creek Basin within Victoria's western uplands (shaded), with rainfall isohyets. Stony Creek Basin relative to the town of Daylesford, height above sea level shown contoured and locations within the basin of the pollen- and diatomite-bearing sections.


142°E
144°E
VICTORIA
Horsham
Bendigo
Loddon River
37°S
37°S
WEST VICTORIAN UPLANDS
SOUTH AUSTRALIA
700
700
600
1000
700
Ballarat
Melbourne
Stony Creek Basin
Hamilton
Glenelg River
Hopkins River
Mt Emu Creek
Geelong
Portland
Colac
1000
N
BASS STRAIT
0
100
kilometres
144°E
650
Old Ballarat Rd
450
600
Creek
Stony
Basin road
Ballan - Daylesford Road
Stony Creek Basin
600
0 250 500 750 1000
metres
Western Victorian Uplands
700 – Annual rainfall (mm)
Basalt
Sandstone and Shale, Ordovician
Lake sediments
600 – Metres asl
# Pollen bearing section
+ Diatomite section with fission track age

fossil leaf impressions, diatoms and sponge spicules attracted early scientific attention (Hart 1904; Orr 1927; Patton 1928; Coulson 1950). A vertical shaft lowered near the southern edge of the basin in 1864 encountered quartz gravels only after penetrating 35m of black clay (Hart 1904), which provides a minimum estimate of the depth of the lacustrine sequence.

The geological origin of the basin is uncertain. However, its simple circular outline, small size, depth of accumulated sediment and proximity to conspicuous eruptive centres in this volcanic region all suggest that the structure may be an explosion crater or maar, although no tuffaceous rocks are evident in the immediate vicinity (Orr 1927; JDH & JMKS pers. obs.).

METHODS

In March, 1999, a trench approximately 3 m in depth was excavated near the centre of the lake deposit. Samples were taken from the exposed vertical section (herein the pollen-bearing section) by hammering in and then extracting 10 x 10 cm metal boxes. Samples were wrapped with polyethylene, and transported to cold storage at the School of Geography and Environmental Science, Monash University.

Additional samples were collected from a 2 m high exposure (herein the diatomite section) of gravelly-mud overlain by 30 cm of diatomite, located in a drainage ditch approximately 50 m southeast of the trench. One sample was sieved and weight-separated to isolate its zircon fraction for analysis by the fission track dating method. The stratigraphic relationship between the diatomite and pollen bearing sections was investigated by augering down through the diatomite section.

Pollen and physical analysis

In the laboratory, 41 one cm^3 subsamples were taken at approximately 6.5 cm intervals for pollen analysis, and 5-10 cm^3 of sediment surrounding each subsample was taken for physical analysis. Organic and carbonate content were estimated by loss on ignition after combustion for two hours at 500° and 1000° C, respectively (Dean 1974). Pollen samples were spiked with a known quantity of exotic *Lycopodium* grains to allow calculation of pollen concentrations, and processed using standard chemical methods involving KOH, acetolysis, and HF (Moore *et al.* 1991), before being desiccated with ethanol and mounted in glycerol on microscope slides.

Pollen was counted routinely at 400x magnification with 1000x used for difficult identifications, under Olympus CH-2 and Zeiss Axiolab compound microscopes. In most cases at least 200 identifiable grains of dry land pollen and fern spore taxa were counted. These grains formed the pollen sum on which percentages of all taxa were calculated. Grains of aquatics, including the fern-ally *Isoetes*, were excluded from the sum. Charcoal particles, defined as angular, opaque particles greater than 10μ, were counted in relation to exotic *Lycopodium* spores on 20 slides.

Pollen identification was assisted by comparison with reference slides, and photos held in the School of Geography and Environmental Science, Monash University and contained in palynological publications on the Cenozoic of the Australian region. Pollen grains and fern spores were identified to the most refined feasible taxonomic level, usually genus or family. Identification of Myrtaceae pollen proved problematic. Despite the phytosociological importance and ecological diversity of the family, its pollen exhibits little morphological variation. Thus while most of the grains attributed to '*Eucalyptus* comp.' were clearly consistent with the modern pollen morphology of that genus, the type also includes grains that may represent both rainforest and sclerophyll genera including *Angophora*, *Melaleuca*, *Acmena* and *Syzygium*. Relatively distinctive verrucate pollen similar to that produced by the rainforest genera *Rhodomyrtus* and *Rhodamnia* was described as 'rainforest Myrtaceae', while psilate, syncolpate 15-20 μm grains of unknown generic affinity were described as 'other Myrtaceae'. Grains that were not clearly *Leptospermum* were attributed to 'myrtaceous shrubs' that may include genera such as *Baeckia* and *Callistemon* as well as some *Melaleuca* species. Within the Podocarpaceae, *Dacrydium* includes grains resembling both New Zealand *D. cupressinum* and New Caledonia *D. guillauminii*.

Zonation of the pollen diagram was carried out using dry land taxa with at least 5% representation in one or more samples. Four statistically significant local pollen zones were distinguished through optimal splitting by information content using PSIMPOLL (Bennett 1998).

Zircon fission-track analysis

Following mineral separation, zircon grains were mounted in FEP teflon, and, after optical-quality polishing, were etched in an eutectic KOH-NaOH melt (Gleadow et al. 1976) at 225°C for ~125 hours. Neutron irradiations were carried out in a well-thermalised flux in the HIFAR reactor, Lucas Heights, Australia. Fission track ages were measured using the external detector method (Gleadow 1981) with Brazil Ruby muscovite being used to record induced tracks. The muscovite detector was etched for 20 minutes in 48%HF at room temperature to reveal the induced tracks. The thermal neutron fluence was monitored by measuring the track density recorded in muscovite attached to pieces of the U3 standard glass. Fission tracks were counted in transmitted light using a dry 100x objective at a total magnification of 1600x. Only zircons with sharp polishing scratches were counted. A total of 64 individual grains were dated. The age of the sample was calculated using the standard fission track age equation using the zeta calibration method (Hurford & Green 1982) and errors were calculated using published methods (Green 1981). A personal zeta calibration factor (for POS) of 87.8±5 (U3) was determined empirically using zircon age standards with independently known ages.

RESULTS

Sediment stratigraphy

The pollen-bearing section exhibited massive to faintly microlaminated, very dark grey or black silty clays with organic content ranging from 10-25% (Fig. 2). Uniformly low (<3%) weight losses after combustion at 1000° C may be attributable to loss of clay lattice water rather than carbonate (Dean 1974) and are not presented. Augering of the diatomite section revealed grey, gravelly mud changing abruptly (over ~10cm) to fine, organic-rich black clay at a depth of 3.4 m below the base of the drainage ditch. Pollen analysis of this black clay suggested a correlation with local pollen zone S-2 or S-3(Fig. 3), implying that the diatomite section sits stratigraphically above the pollen-bearing section.

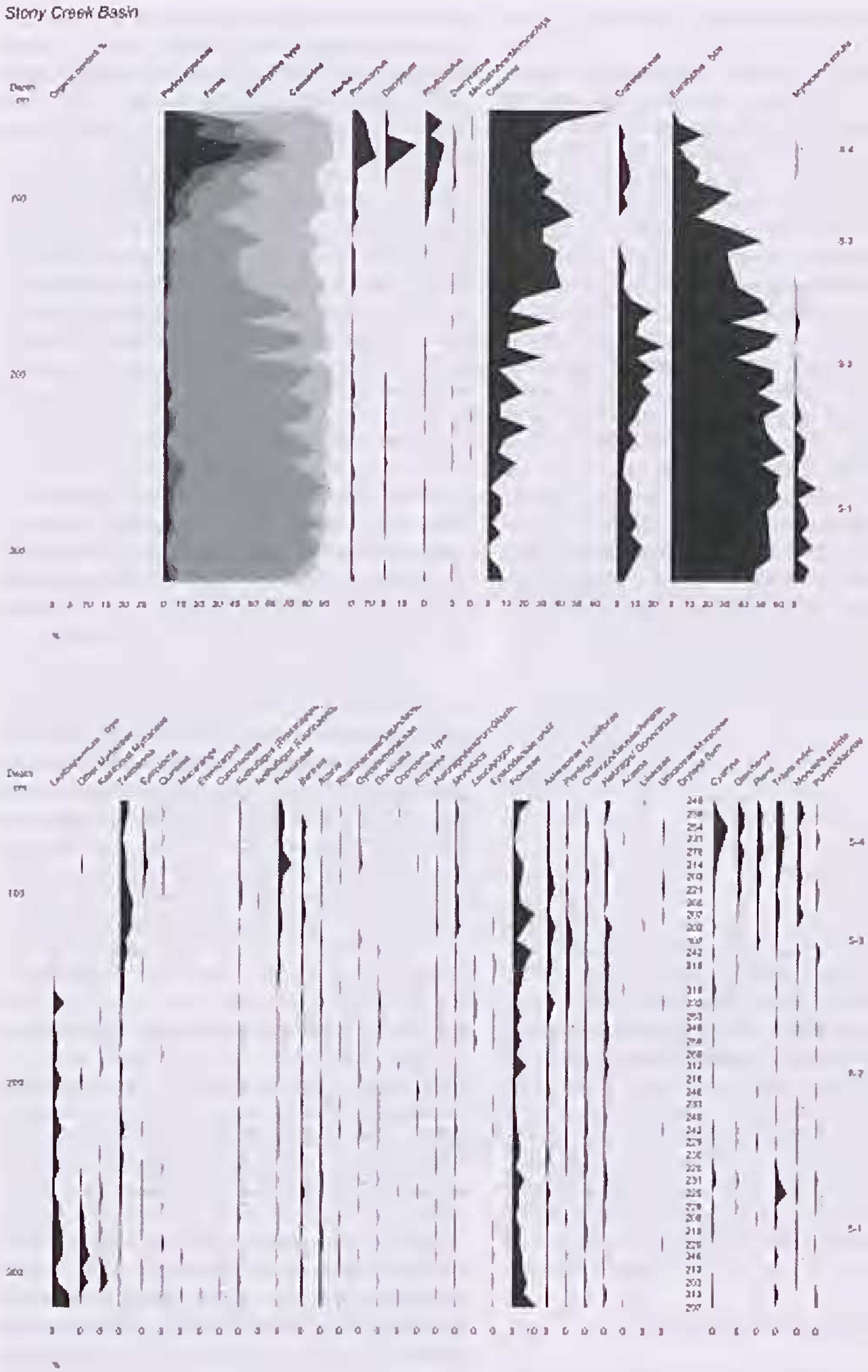
Description of the pollen diagram

Pollen and spore taxon percentages, organic matter and moisture content, charcoal and pollen concentrations, and charcoal/pollen ratios are shown in relation to the established zonation on Fig. 2. Also included is a summary diagram of ratios between Podocarpaceae, fern spores, *Eucalyptus* type, *Casuarina* and herbs including Poaceae.

Zone S-1 (318-235 cm): *Eucalyptus* type is consistently the dominant dry land pollen type, never falling below 45% of the sum. Non-eucalypt Myrtaceae are best represented, and most diverse, in this zone. Casuarinaceae and Cupressaceae have low percentages, and herbaceous taxa are poorly represented. *Acacia* is most consistently represented in this zone, and *Banksia* is represented by a small number of grains in most samples. Trace values are present for a variety of dry land shrubs and trees from both open forest and rainforest. Several rainforest taxa, viz. *Nothofagus* (Brassospora), *Symplocos*, *Quintinia*, *Macaranga-Mallotus* and *Elaeocarpus* have some representation. Herbaceous pollen, composed almost entirely of Poaceae, have relatively low values as do the aquatics, apart from a single peak in Cyperaceae. Charcoal and pollen concentrations are highest in this zone, and the charcoal:pollen ratio is erratic.

Zone S-2 (234-155 cm): *Eucalyptus* type remains the dominant type throughout, decreasing only slightly towards the top. Rainforest Myrtaceae and other Myrtaceae nearly disappear near the base of this zone, myrtaceous shrubs decrease to trace levels towards the top of the zone, while *Leptospermum* maintains values only slightly lower than those in zone S-1. Cupressaceae achieves its highest percentages within this zone (10-20%), while Casuarinaceae percentages rise steeply towards the top of the zone. Pollen values of herbaceous taxa remain low, but *Plantago*, Asteraceae (Tubuliflorae) and *Haloragis* are more abundant and more consistently represented than in zone S-1. Sclerophyll tree and shrub taxa, such as *Acacia*, *Banksia*, Proteaceae, *Haloragodendron*/*Glischrocaryon* and *Dodonaea*, are consistently represented. Aquatic values remain low. Both charcoal and pollen concentrations decline from zone S-1, but the charcoal:pollen ratio rises to its highest values in this zone.

Zone S-3 (154-95 cm): This zone is marked by a dramatic peak in the shallow-water aquatic *Isoetes* (which played no role in zone definition) accompanied by distinctly higher values in other aquatic and swamp taxa, namely Restionaceae, Cyperaceae and *Triglochin*/*Typha*. Dominance of the


Stony Creek Basin
Depth
100
200
300
S-4
S-3
S-2
S-1
%

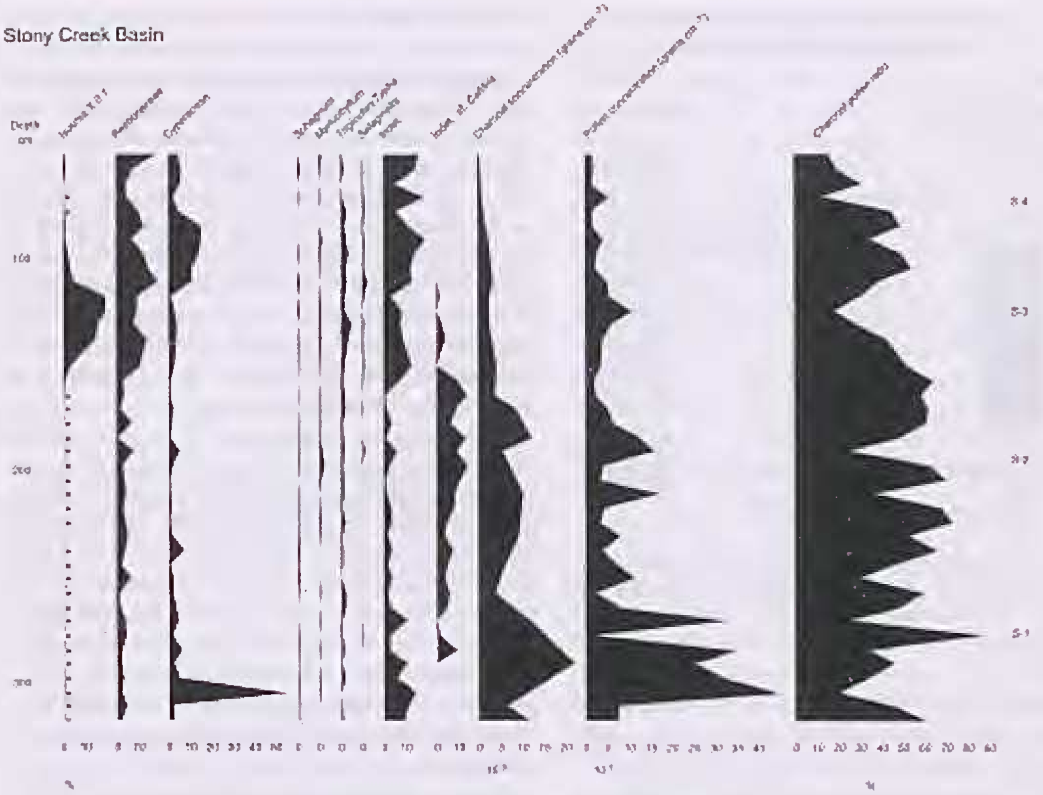


Fig. 2. Stony Creek Basin pollen percentage diagram plotted against depth. Percentages are relative to the total pollen and spore sum, excluding aquatic pollen.

pollen sum is shared by Casuarinaceae and *Eucalyptus* type, although the latter declines towards the top of the zone. Cupressaceae is very low at the base of the zone, then disappears from the record to return towards the top of the zone. *Podocarpus*, though still less than 5% of the pollen sum, is slightly better represented than at any time previously, while *Phyllocladus*, absent in the lower half of the zone, is increasingly represented in the upper half. The latter pattern is evident also in *Tasmannia*, *Monotoca*, Proteaceae and by most fern spores. The opposite trend is exhibited by Poaceae, Asteraceae, *Plantago* and *Haloragis*, which are all best represented in this zone, but then drop to low levels near the top of the zone. Concentrations of charcoal are low while pollen concentration peaks in the middle of the zone.

Zone S-4 (94-51 cm): Casuarinaceae dominates the pollen sum, while *Eucalyptus* type declines through the zone, vanishing completely in the uppermost sample. Podocarpaceae and Cupressaceae increase in importance, then decline to low levels or disappear near or at the top of the zone. Podocarpaceae, fern spores, Proteaceae, including *Banksia*, and *Symplocos* are all best represented in this zone. Herb and shrub taxa are poorly represented except for *Monotoca*. Of the aquatic and swamp taxa, Restionaceae and Cyperaceae are relatively well represented but at lower levels than in the previous zone. The uppermost sample at 51 cm is very distinctive, being marked by high values for Casuarinaceae, *Tasmannia*, Proteaceae, Poaceae, *Haloragis*, some fern types and Restionaceae, and the complete absence of *Eucalyptus* comp. and most Podocarpaceae. Pollen and charcoal concentrations, and the charcoal:pollen ratio, are generally low in this zone.

Fission track results

The zircon fission track ages for the sample from the diatomite section are presented in Fig. 4. Complete analytical results for the 64 grains analysed from this sample are shown in Table 1 and single-grain age

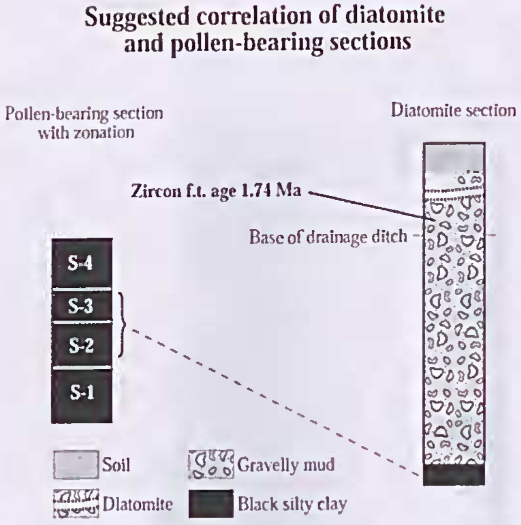


Fig. 3: Stratigraphy of the pollen-bearing section and the diatom section, showing the location from which detrital zircons were recovered, and suggested correlation of the diatomite section with zones S2-S3 of the pollen bearing section.

distributions (in the form of radial plots) are presented in Fig. 4A, B.

An overall age of 6.7±0.9 Ma was calculated for the 64 individual grains dated. However, as shown in Fig. 4A, the sample contained at least three distinct grain-age populations, indicating that the unit sampled from the diatomite section had been provenanced from multiple source terrains. Therefore, in order to best estimate the age of deposition of the diatomite section, the grains from the older two populations were statistically removed before a final age calculation was made. Following this, the sample yielded a date of ~1.74±0.16 Ma (Fig. 4B).

AGE AND DURATION OF THE SEQUENCE

The timing of sediment deposition in Stony Creek Basin can be estimated in two ways: interpretation of the fission track age from detrital zircons found within the diatomite section, and by comparison with southeastern Australian regional pollen and spore stratigraphies.

Fission track ages of detrital zircons from the diatomite section indicate that this unit probably was deposited around 1.74±0.16 Ma. As the pollen-bearing black clays underlie the diatomite, they must have been deposited prior to this time. The abrupt transition between the two units suggests that their contact may represent an erosional hiatus. Consequently the age of the pollen record is uncertain. It might be assumed, however, that any hiatus would be of short duration considering that small, deep maar lakes typically fill with sediment in only some 200-300 kyr, in tectonically relatively stable regions such as the western plains of Victoria (Wagstaff et al. 2001) and the Atherton Tableland of northeast Queensland (Kershaw et al. 1991a). Thus deposition of the pollen-bearing black clays is unlikely to predate deposition of the diatomite section by more than this, and probably occurred towards the end of the Late Pliocene (2.6-1.78 Ma).

Comparison with late Cenozoic pollen stratigraphies derived from the marginal marine Murray and offshore Gippsland Basins (Macphail and Truswell 1989, 1993; Macphail 1997, 1999) suggest deposition may have occurred as early as the Late Miocene-Early Pliocene, when SCB rainforest taxa such as *Dacrydium*, *Dacrycarpus* and *Symplocos* disappear from Murray Basin sequences, *Nothofagus* Brassospora first declines to trace levels, and some open forest taxa which contribute to the SCB record, such as *Amperea* (*Rhoipites ampereaformis*), *Monotoca* (*Monotocidites galeatus*) and *Leptospermum* first appear (Macphail and Truswell 1993). A minimum age of Late Pliocene is indicated by the consistent trace presence of Brassospora, which is absent completely from younger strata within both the Murray and Gippsland Basins, and by the absence from SCB of the *Cossinia arcuata*-type (*Tubulifloridites pleistocenicus*), the first consistent appearance of which defines the base of the Late Pliocene in both Murray and Gippsland Basins (Macphail 1997, 1999).

However, the dominance of SCB local pollen zones S-2 and S-3 by sclerophyll vegetation associated with herb and shrub genera including *Pimelea* (*Thymelaepollis* sp.) and *Plantago*, both first recorded for southeastern Australia in the Late Pliocene (Macphail *et al.*1995; Macphail 1999), and *Pomaderris*, common in southeastern Australian modern pollen rain (Macphail 1981; Kershaw *et al.* 1994b) and Early-Late Quaternary records (D'Costa and Kershaw 1997; Wagstaff *et al.* 2001) but apparently unknown(?) from the Tertiary (Stover & Partridge 1973; Martin 1987; Macphail & Truswell 1993; Macphail *et al.* 1995), suggest that the sequence is no older than terminal Late Pliocene. Furthermore, the apparent close temporal juxtaposition of rainforest angiosperms and gymnosperms such as *Symplocos*, *Quintinia*, *Podocarpus*, *Phyllocladus*, *Dacrydium* and *Dacrycarpus* that are extinct or highly restricted in the region today, with *Callitris*-, *Eucalyptus*- and Casuarinaceae-dominated vegetation, evokes a period of 'transitional' Tertiary-Quaternary vegetation comparable to Casuarinaceae-Podocarpaceae dominated assemblages attributed to the Late Pliocene of the palaeomagnetically dated Lake George record (McEwan Mason 1989; 1991). These juxtapositions of extinct and extant taxa with contrasting ecologies cannot be explained by reworking of fossil palynomorphs because there are no known polliniferous older rocks in the catchment of the basin. The trace quantities of *Nothofagus* (Brassospora) at Stony Creek Basin contrast with Middle Pliocene assemblages from Lake George, and Late Pliocene assemblages from western Tasmania (Macphail et al. 1995), in which Brassospora was still a substantial component, suggesting that Stony Creek Basin is coeval with or younger than these assemblages.

If the age of the SCB sequence is considered latest Pliocene, the absence of the *Cassinia arcuata*-type (*T. pleistocenicus*) demands explanation. Given the small size of the Stony Creek Basin palaeolake, this absence may simply reflect the absence of source plants from a restricted upland pollen catchment. Similar contrasts between upland and lowland basins occur in the Late Quaternary where, for example, the *C. arcuata*-type is virtually absent from a swamp record spanning the last glacial cycle at Wyelangta, in the Otway Ranges (McKenzie & Kershaw 2000), despite the proximity of these ranges to the Victorian western plains where the pollen type constitutes up to 20% of pollen sums during glacial episodes ranging from the latest Early Pleistocene up to the last glacial maximum (D'Costa et al, 1989; Harle et al. 1999; Wagstaff et al. 2001). The absence at Stony Creek Basin of the *C. arcuata*-type may similarly reflect the inability of lowland pollen to significantly penetrate pollen assemblages within small, upland lakes with forested catchments.

The temporal resolution of the pollen record, and the length of the interval it represents, is uncertain. However, sedimentation rates in maar lakes possessing good chronological control, both in Australia (Kershaw 1986; Harle et al. 1999; Wagstaff et al.2001) and in Europe (Leroy & Seret 1992; Williams et al. 1996; Zolitschka and Negendank 1996; Willis et al. 1999) are relatively uniform, varying only between about 2 and 7 kyr m^{-1}. On this basis, the 270 cm of sediment analysed here may represent 6 kyr - 19 kyr.

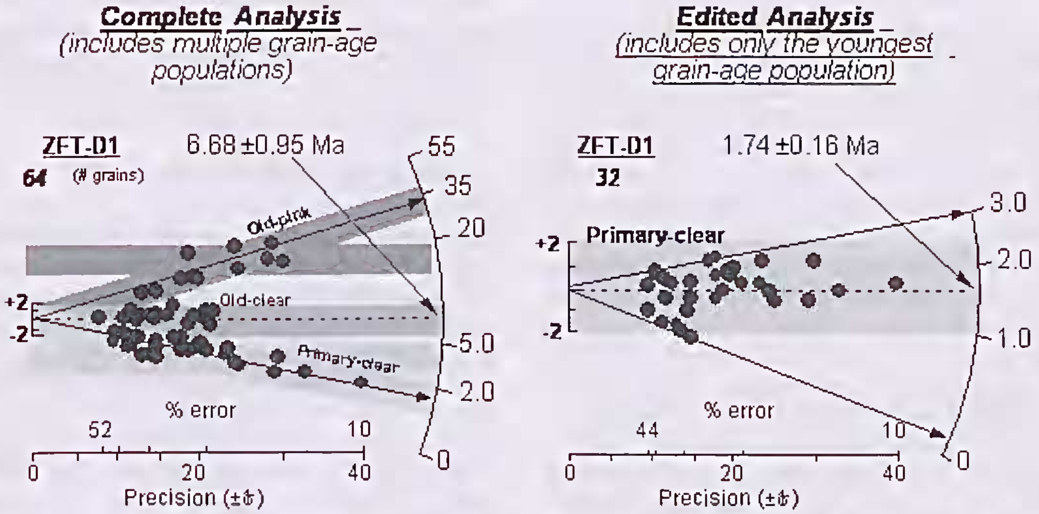


Fig. 4A, B. Single-grain age results in the form of radial plots from the sample dated from the diatomite section. The first plot (Fig. 4A) shows all of the single-grain ages for the sample. These break down into three distinct age populations: 1) old-pink grains, 2) old-clear grains, and 3) young-clear grains. The second plot (Fig. 4B) shows only the ages from the young-clear population of grains. The age of this population of grains of ~1.74 Ma is interpreted to represent the minimum age of deposition of the unit. On radial plots, each age has unit standard error (±2σ) on the y-axis, its actual precision is indicated on the x-axis, and its age is read by extrapolating a line from the 0-point through the plotted point to the logarithmic age scale on the right perimeter. Further details presented in the text.

PALAEOENVIRONMENTAL RECONSTRUCTION

Vegetation and environments

During zone S-1, the deposition of fine organic mud and low representation of aquatic pollen suggests a deep lake local environment with only a narrow fringe of swamp vegetation. Eucalypt forests, with other sclerophyll elements such as Casuarinaceae, *Callitris, Acacia* and *Banksia,* dominated the pollen catchment, while the presence of small quantities of poorly dispersed pollen similar to that of taxa such as rainforest Myrtaceae implies that these forests included a rainforest component or understorey. Modern climatic preferences of the rainforest trees *Rhodamnia*, *Rhodomyrtus*, *Macaranga-Mallotus*, *Symplocos* and *Quintinia* together suggest these contributed to warm temperature/subtropical (mesotherm) rainforest. Subsequent loss of most of these rainforest taxa in the upper half of the zone could reflect one or more of a number of climate changes including regional drying, temperature reduction, altered seasonality and increased climatic variability. The lack of response of aquatic pollen values together with the persistence of mesic understorey taxa such as *Tasmannia* and ferns, indicative of cool but moist conditions, suggests that a temperature reduction was a major cause.

Eucalypt dominance continued through zone S-2. Some change in the vegetation is indicated by the expansion of *Callitris* and to some extent Casuarinaceae, along with shrubs such as *Dodonaea*, *Coprosma*, *Haloragodendron* and the Epacridaceae, that could indicate some drying, although this is not supported by values of aquatic taxa and herbs that remain low, suggesting the maintenance of deep water conditions. Alternatively, increased lake level variability may have disrupted marginal swamp vegetation. Regional fire frequency and/or intensity was greatest during this time, which is perhaps consistent with some variability in the pollen representation of major taxa, and supports the proposal of more variable climatic conditions.

The dramatic increase in aquatics in zone S-3, notably *Isoetes* but also *Typha*/*Triglochin*, Restionaceae and Cyperaceae, indicates expansion of shallow water habitat most likely due to a substantial reduction in lake water level. The synchronous expansion of herbs, notably Poaceae, Asteraceae, *Plantago* and *Haloragis*, suggests this lowering of water levels was predominantly a response to regionally reduced effective precipitation. Eucalypt forests with associated shrubs were increasingly replaced by Casuarinaceae dominated communities. Decreasing charcoal and dryland pollen concentrations could reflect increased sediment deposition with greater aquatic plant productivity.

In the period represented by the latter part of zone S-3 and zone S-4, *Eucalyptus* forests declined and eventually disappeared from the area around the basin. Shrub and herb taxa characteristic of open vegetation also declined, in response to expansion of *Casuarina-Allocasuarina* forest and rainforest which included the gymnosperms *Podocarpus*, *Phyllocladus*, *Dacrydium* and perhaps also *Dacrycarpus*, despite its low pollen values. *Quintinia* and *Symplocos* also contributed to this western uplands rainforest, as did an understorey of ferns. The co-occurrence of *Casuarina* or *Allocasuarina* with diverse Podocarpaceae may reflect edaphic and topographic niche differentiation. The expansion of rainforest and reduction in more open eucalypt vegetation suggests increased precipitation, and/or reduced importance of fire. Support for high rainfall is also provided by a reduction in aquatic pollen, especially in the middle of zone S-4. The generally higher aquatic pollen component towards the top of the record may reflect general shallowing of the lake due to sedimentation rather than simply effectively lower rainfall. The absence of zone S-1 rainforest taxa of mesotherm affinities, and their replacement by Podocarpaceae dominated rainforest, suggests that zone S-4 rainforest was cool temperate (microthermal).

Quantitative palaeoclimate estimates

The Stony Creek Basin data provide evidence for the successive development of discrete climatic episodes during the Late Pliocene in Victoria's western uplands. Quantification of the climate prevailing during these episodes may be attempted by reference to the climatic tolerances of inferred nearest living relatives (Hill and Scriven 1997; Jordan 1997a) of the fossil pollen taxa. However, since the fossil pollen generally has not been identified below the genus level, the number of species with which a fossil type must be compared may be large, and the resulting inferred climatic space correspondingly imprecise (Martin 1997). This problem is especially acute in zones S-2 and S-3 where dominant genera or pairs of closely related genera (eg. *Eucalyptus*, *Callitris*, *Casuarina*/*Allocasuarina*, *Gonocarpus*/*Haloragis*) exhibit uninformative bioclimatic profiles as a consequence of extensive, continent-wide distributions. Quantification of palaeoclimate in these zones is therefore difficult. By contrast, rainforest genera or generic groups which contribute to zones S-1 and S-4 can effectively constrain Late Pliocene western uplands palaeoclimate. This is possible despite the large number of Australasian species in some of these genera (eg. *Macaranga*/*Mallotus*, *Podocarpus*) both because of the clear differentiation of southeastern Australian rainforest into microtherm (4-14°C mean annual temperature- MAT) and mesotherm (14-22°C MAT) types (Nix 1982) and because of the relatively high minimum precipitation requirements exhibited by Australian rainforest generally.

Rainforest pollen types present in zone S-1 (eg. *Rhodamnia*/*Rhodomyrtus* types, *Macaranga*/*Mallotus* and *Elaeocarpus*) suggest the occurrence of at least limited local stands of mesotherm rainforest. Using the structural/environmental rainforest typology of Webb (1968), these taxa imply the presence of evergreen notophyll vine forest, which can serve as an approximate vegetation model from which an estimate of climate can be made based on a bioclimatic analysis of Australian rainforests by Nix (1991). Climate averages for this rainforest type are MAT around 18°C, with precipitation around 1650 mm. A conservative climate estimate for zone S-1 suggests that MAT was at least the 14°C minimum for all Australian mesotherm rainforests, and annual precipitation was ≈ 950 mm (Nix 1982, 1991).

The rainforest pollen assemblage present in zone S-4 (*Podocarpus*, *Dacrydium*, *Phyllocladus*, *Dacrycarpus*, *Tasmannia*) implies the presence of microtherm rainforest, by comparison with the ecological and climatic habitats of Podocarpaceae in southeastern Australia, Tasmania and New Zealand (Kershaw & McGlone 1995; Ogden & Stuart 1995). The assemblage has no analogue in Australian vegetation today, but the climate during deposition of zone S-4 may be estimated by comparison with Webb's (1968) microtherm Evergreen microphyll fern forest. Although this forest type typically is dominated by *Nothofagus cunninghamii*, its widespread distribution from Tasmania to northern New South Wales, and the inclusion in Tasmania of *Phyllocladus aspleniifolius* and other Podocarpaceae, suggest that its bioclimate may provide a first approximation of the climate of zone S-4. Climate averages (Table 2) for this rainforest type include MAT around 12°C, with precipitation around 1250 mm. A conservative estimate for zone S-4 suggests that MAT did not exceed the 14°C maximum for all Australian microtherm forests, and annual

Table 1. Fission track analytical results.

Number of grains	Standard track density ($x10^5 cm^{-2}$)	Fossil track density ($x10^5 cm^{-2}$)	Induced track density ($x10^6 cm^{-2}$)	Chi squared probability	Uranium (ppm)	Fission track age (Ma±1σ)
Complete anaysis - includes all three zircon populations						
64	*6.982*	*9.713*	*4.091*	*0.0*	*304.7*	*6.68±0.95*
	(2724)	*(1080)*	*(4549)*			
Oldest grain-age populatian (old-pink zircon grains)						
11	*6.982*	*36.25*	*3.817*	*3.1*	*284.2*	*29.2±2.3*
	(2724)	(645)	(679)			
Middle grain-age papulatian (old-clear zircon grains)						
21	6.982	8.779	3.310	99.5	246.5	8.13±0.64
	(2724)	(274)	(1033)			
Youngest population (young-clear zircon grains)						
32	6.982	2.589	4.562	85.8	339.8	1.74±0.16
	(2724)	(161)	(2837)			

Brackets show number of tracks counted. Standard and induced track densities measured on mica external detectors (g=0.5), and fossil track densities on internal mineral surfaces. Zircon ages calculated using ζ=87.8±5 for dosimeter glass U3 (analyst: P. O'Sullivan) precipitation was ≥850 mm (Nix 1991).

Comparison of these estimates with modern climate at Stony Creek Basin (Table 2) suggests that during deposition of zone S-4, MAT was similar to today (11.1°C). By contrast, temperatures during deposition of zone S-1 were at least 3°C warmer (≥14°C) than today. The minimum estimates for annual precipitation during zones S-1 and S-4 suggest that modern precipitation at Stony Creek Basin (868 mm) may be marginally adequate to support some rainforest types, although the driest quarter (summer) rainfall of only 133 mm apparently is lower than summer minima for all Australian rainforest types (Nix 1991)(Table 2). Thus Late Pliocene western uplands climates appear to have been wetter than today, particularly during summer.

There are, however, additional potential constraints on acceptance of these quantitative palaeoclimatic estimates. First, rainforest taxa may overestimate regional precipitation if source plants were confined to sheltered, moist microclimates (Carpenter and Horwitz 1988; Demko *et al.* 1998). However, rainforest in southeastern Australia frequently is confined to sheltered microclimates in otherwise fire prone landscapes (Busby 1986; Bowman 2000), and such marginal stands are represented in the bioclimatic profiles (Nix 1991).

Second, extinctions of rainforest taxa are documented as recently as the Early-Middle Pleistocene in western Tasmania (Jordan 1995a,b; 1997a,b), where microfossil and macrofossil assemblages dominated by extant microtherm species also include extinct species belonging to higher taxa (e.g., *Quintinia*, *Austromyrtus*, *Symplocos*, Lauraceae) now confined in Australia to lower latitude, meso- and megatherm habitats. Jordan (1997a) showed that these "apparent" mesotherms were all extinct species and/or the bioclimatic profiles of their living mesotherm relatives were anomalous within predominantly microtherm assemblages. He thus argued that the apparent mesotherms were in fact microtherms with climatic tolerances similar to those of extant Tasmanian rainforest.

If this pattern is a general one, it is possible that the source plants of the apparently mesotherm pollen types at Stony Creek Basin were in fact microtherms, and their presence may not imply that Late Pliocene MAT was significantly different from modern microtherm MAT at SCB. However, in contrast to Jordan's (1997a) fossil assemblages dominated by extant microtherm species, the zone S-1 rainforest assemblage contains no obvious climate anomalies, but is composed of "apparent" mesotherms (e.g. rainforest Myrtaceae, *Macaranga-Mallotus*, Cunoniaceae, *Elaeocarpus*). Possible exceptions include *Symplocos* and *Quintinia*, which Jordan (1997a) believed may have included microtherm species in the Tasmanian Early Pleistocene. The occurrence of both genera in both zones S-1 and S-4 may reflect close altitudinal juxtaposition of meso- and microtherm communities, or may reflect the involvement of more than one species in each genus. Nevertheless, in the absence of macrofossil evidence identifiable to the species level, there appears no reason to reject the simplest interpretation that the assemblage reflects the presence of mesotherm rainforest taxa during the Late Pliocene in Victoria's western uplands.

Table 2. Selected bioclimatic attributes of the primary rainforest groups Evergreen notophyll vine forest, Evergreen microphyll fern forest, and modern climate at Stony Creek Basin (rainforest data after Nix 1991; Stony Creek Basin data generated in BIOCLIM).

	Annual mean temperature (°C)	*Wettest quarter mean temp.*	*Driest quarter mean temp.*	*Annual mean rainfall (mm)*	*Wettest quarter mean rainfall*	*Driest qtr mean rainfall*
Evergreen notophyll vine forest	17.9 ±2.8	21.8 ±2.3	14.7 ±3.9	1657 ±603	792 ±386	183 ±62
Evergreen microphyll fern forest	12.0 ±1.9	13.0 ±5.0	11.5 ±4.0	1255 ±430	429 ±211	214 ±44
Stony Creek Basin	11.1	5.8	16.5	868	296	133

It is noteworthy that marine oxygen isotope records provide little support for warmer than Holocene global mean temperatures for any time since about 2.6 Ma (Shackleton *et al.* 1990, 1995). If, as argued by Kershaw (1997), lower rainfall and temperature limits for many Australian rainforest taxa have been truncated by glacial aridity and fire, it may be possible that Late Pliocene growth of "mesotherm" rainforest taxa in Victoria's western uplands, rather than reflecting elevated Late Pliocene MAT, depended upon regional effects, perhaps related to rainfall seasonality and its effects on fire frequency.

IMPLICATIONS FOR REGIONAL VEGETATION AND CLIMATE RECONSTRUCTIONS

Implications of the Stony Creek Basin record for regional climate and vegetation reconstruction, combining pollen data associated with fission track dated sediment, are twofold:

In the first place, patterns of change in the record could suggest that the vegetation and aquatic environments of Stony Creek Basin are very sensitive to climate changes of broad regional significance. While it may be premature to attribute concepts of glacial climate stages to the pollen assemblages, it is possible that the sequence represents part of a climate cycle resulting from orbital forcing, with zone S-1 representing a moist, mesothermal 'interglacial' assemblage, S-2 and S-3 representing cooling 'glacial' conditions peaking in S-3, and S-4 representing a moist, microthermal 'interstadial' period. Preliminary analysis of an extended 40m long core collected recently from the basin (JMKS, unpublished data) does confirm the cyclic nature of vegetation succession observed in these top three metres.

Secondly, the presence of rainforest taxa outside the modern range of rainforest in the SCB record implies the persistence of high, particularly summer, rainfall, at least during "interglacial" or "interstadial" intervals, in Victoria's western uplands during the latest Tertiary. Bowler (1982) suggested that evolution of Australian Cenozoic climate involved a late Neogene shift from summer-dominant to winter-dominant rainfall across southern Australia. Kershaw *et al.* (1991b) and Truswell (1993) considered this shift may partly explain the final demise of many rainforest taxa in southern Australia which are now extinct or confined to Australia's east coast. The Stony Creek Basin data imply that such a shift may have been more protracted, and more complex, than previously considered, as it apparently had not fully run its course near the end of the Pliocene.

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